

# NEUTRINO DARK MATTER

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There is a puzzling contradiction: direct observations favor a low-mass density universe, but the only model which fits universe structure over more than three orders of magnitude in distance scale has a mix of hot (neutrino) and cold dark matter constituting a critical density universe. If all present indications for neutrino mass are valid, that hot dark matter is shared by two neutrino species ( $\nu_\mu$  and  $\nu_\tau$ ). These results also require at least one light sterile neutrino to exist to explain the solar  $\nu_e$  deficit ( $\nu_e \rightarrow \nu_s$ ), so that  $\nu_\mu \rightarrow \nu_\tau$  accounts for the atmospheric neutrino anomaly, with  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  being observed in the LSND experiment. This experiment, when analyzed appropriately, does not conflict with any others and is compatible with the mass difference needed for dark matter. Support for this mass pattern is provided by the need for a sterile neutrino to make possible heavy-element nucleosynthesis in supernovae.

## 1 The Dark Matter Conundrum

Observations of high-redshift Type 1a supernovae, evolution of galaxy clusters, high baryon content of galaxies, lensing arcs in clusters, dynamical estimates from infrared galaxy surveys, and especially the existence of galaxies at very high redshift<sup>1</sup> all indicate that the matter density of the universe is less than critical (i.e.,  $\Omega_m < 1$ ). On the other hand, the only model which fits the data on the cosmic microwave background anisotropies and the large-scale distribution of galaxies and clusters is a model (CHDM) having  $\Omega_m = 1$ , with 70% cold dark matter, 20% hot dark matter, and 10% baryonic matter.<sup>2</sup> These structure data covering three orders of magnitude in distance scale seemingly exclude models of an open universe (low  $\Omega_m$ ) or one adding a cosmological constant ( $\Lambda$ ) to provide critical energy density ( $\Omega_m + \Omega_\Lambda = 1$ ), since the fit probabilities are  $\sim 10^{-4}$ – $10^{-5}$ . Extending the fits another order of magnitude into the smaller scale non-linear regime makes the discrepancy between CHDM and the low  $\Omega_m$  models even greater.<sup>3</sup> Another measure of structure, the probability of voids, also strongly favors CHDM over the low  $\Omega_m$  models.<sup>4</sup> Adding some neutrinos to the latter helps only a little.<sup>5</sup>

This clearly is an important conflict which may get resolved by better observations or by the discovery of some new factor which reconciles the observations. At this time for help in knowing whether neutrino dark matter exists, we must turn to observations of neutrino mass.

## 2 Evidence for Neutrino Mass

Three types of observation give evidence for neutrino mass. Two of these are of importance here only in establishing a likely pattern of neutrino masses, and hence these will be treated cursorily, but the third is of direct relevance for hot dark matter and will therefore be discussed more thoroughly.

The first is the deficit of electron neutrinos from the sun observed by four experiments. The four are of three types, covering different  $\nu_e$  energy ranges, and hence sampling different contributions from various nuclear processes producing neutrinos. These show an energy-dependent discrepancy exemplified by an apparent lack (the best fit being a negative flux) of neutrinos from  ${}^7\text{Be}$  and a finite flux from  ${}^8\text{B}$  neutrinos, yet  ${}^8\text{B}$  is produced by  ${}^7\text{Be} + \text{p} \rightarrow {}^8\text{B} + \gamma$ . This problem cannot be avoided by one of the experiments being wrong. A good solution is provided if the  $\nu_e$  oscillates into  $\nu_\mu$ ,  $\nu_\tau$ , or  $\nu_s$ , a sterile neutrino. While this can be a vacuum oscillation, requiring a mass-squared difference  $\Delta m_{ei}^2 \sim 10^{-10} \text{ eV}^2$  and large mixing between  $\nu_e$  and the other neutrino, more likely is a matter-enhanced MSW<sup>6</sup> type of oscillation. For a  $\nu_\mu$  or  $\nu_\tau$  final state,  $\Delta m_{ei}^2 \sim 10^{-5} \text{ eV}^2$  and mixings either  $\sin^2 2\theta_{ei} \sim 6 \times 10^{-3}$  or  $\sim 0.6$ , while only the former is allowed for  $\nu_s$ .

The second observation explainable by oscillations and hence providing evidence for neutrino mass has now been furnished by three water Cherenkov detectors and two tracking calorimeters. The ratio of  $\nu_\mu$  to  $\nu_e$  produced in the atmosphere is found to be roughly half that expected. These underground experiments observe the  $\mu$  and  $e$  products and utilize  $R = (\mu/e)_{\text{Data}}/(\mu/e)_{\text{Calc.}}$  to reduce flux uncertainties. While the statistical evidence for  $R$  being less than unity is now quite compelling, it is the difference in the angular distribution of the  $\mu$  and  $e$  events which provides the primary evidence that the explanation is neutrino oscillations, giving  $\Delta m_{\mu i}^2 \sim 2 \times 10^{-3} \text{ eV}^2$  and  $\sin^2 2\theta_{\mu i} \sim 1$ . These angular distributions, as well as lack of  $\nu_e$  disappearance observed in a nuclear reactor experiment,<sup>7</sup> rule out  $\nu_\mu \rightarrow \nu_e$  as the predominant process. Quite unlikely is a  $\nu_\mu \rightarrow \nu_s$  explanation, since the large mixing angle would cause the sterile neutrino to be brought into equilibrium in the early universe, providing a fourth neutrino which would alter the expansion rate in the era of nucleosynthesis, spoiling the agreement between calculations and the observed abundances of light elements. There is now fair concordance between  ${}^4\text{He}$  abundance values<sup>8</sup> and the primordial D/H ratio,<sup>9</sup> reinstating the three-neutrino limit. A possible way<sup>10</sup> around this appears to be ruled out.<sup>11</sup> Thus the only viable explanation has  $\nu_\mu \rightarrow \nu_\tau$  as the dominant process.

The third evidence for neutrino mass is from the LSND accelerator experiment, and the mass difference observed is directly relevant for the issue of

neutrino dark matter. This experiment used a decay-in-flight  $\nu_\mu$  beam of up to  $\sim 180$  MeV from  $\pi^+ \rightarrow \mu^+ \nu_\mu$  and a decay-at-rest  $\bar{\nu}_\mu$  beam of less than 53 MeV from the subsequent  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ . The 1993+1994+1995 data sets<sup>12</sup> included 22 events of the type  $\bar{\nu}_\mu p \rightarrow e^+ n$ , expected from  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ , which was based on identifying an electron using Cherenkov and scintillation light that was tightly correlated with a  $\gamma$  ( $< 0.6\%$  accidental rate) from  $np \rightarrow d\gamma$  (2.2 MeV). Only  $4.6 \pm 0.6$  such events were expected from backgrounds. The chance that these data, using a water target, result from a fluctuation is  $4 \times 10^{-8}$ . Note especially that these data were restricted to the energy range 36 to 60 MeV to stay below the  $\bar{\nu}_\mu$  endpoint and to stay above the region where backgrounds are high due to the  $\nu_e {}^{12}\text{C} \rightarrow e^- X$  reaction. In plotting  $\Delta m^2$  vs.  $\sin^2 2\theta$ , however, events down to 20 MeV were used to increase the range of  $E/L$ , the ratio of the neutrino's energy to its distance from the target to detection. This was done because the plot employed was intended to show the favored regions of  $\Delta m^2$ , and all information about each event was used. A likelihood analysis was utilized with contours which would be 90% and 99% likelihood levels, if this were a Gaussian likelihood distribution, which it is not because its integral is infinite. Those contours have been widely misinterpreted as confidence levels—which they certainly are not—because they were plotted along with confidence-level limits from other experiments. The comparison of LSND “favored regions” contours with confidence-level limits, especially because of the use of the 20–36 MeV region for the LSND data, has led to totally incorrect conclusions.

In particular, in the summer of 1998 when the KARMEN<sup>13</sup> experiment with improved shielding was observing no events, such a comparison was often said to rule out the LSND result. While KARMEN is reported now to have observed three events, making their results less exclusive, we use here the zero-event results of last summer to illustrate the difference made by a fairer comparison of the experiments analyzed by the same (Bayesian) method. To do this it is necessary not to use the full  $E/L$  information, so this is not the way to determine favored regions of  $\Delta m^2$ . Figure 1 still shows large regions of conflict if the LSND data from 1993 through 1997 are used for the full 20–60 MeV range of electron energies. On the other hand, if the region originally used to establish an effect (36–60 MeV) is used, excluding the higher background 20–36 MeV region, then Fig. 2 shows no conflict over a very large  $\Delta m^2$  range. The 1996 through 1998 data adds 50% more beam-on events to the 36–60 MeV data but makes the total beam-off background 2.5 times worse because data-taking was parasitic at a slow rate using an iron target. Especially if the 20–36 MeV region is used, the decreased signal/background ratio in the newer data distorts the energy spectrum, making the higher  $\Delta m^2$  values desirable for dark

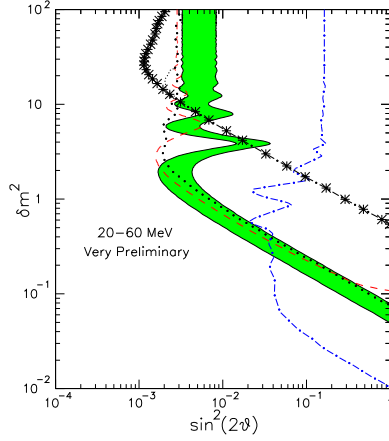


Figure 1: LSND upper and lower 90% Bayesian confidence limits for  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  oscillations using 1993-1997 data with  $20 < E_e < 60$  MeV. Also shown is the 90% Bayesian confidence upper limit from KARMEN as of summer, 1998 (dashed), as well as upper limits from NOMAD (dash-dot-star), E776 (dotted), and Bugey (dash-dot).

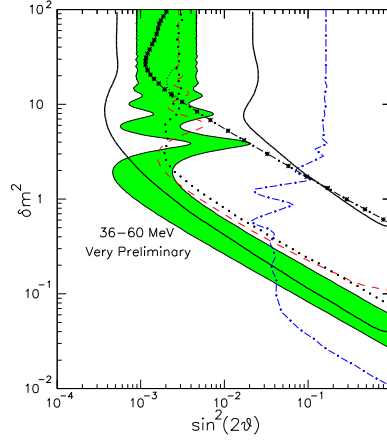


Figure 2: Same as Figure 1, but from  $36 < E_e < 60$  MeV data. The added curves show the 80% confidence band for the LSND  $\nu_\mu \rightarrow \nu_e$  result.

matter erroneously appear less likely.

Also shown in Fig. 2 is the LSND  $\nu_\mu \rightarrow \nu_e$  result<sup>14</sup> which although quite broad tends to favor these higher  $\Delta m^2$  values. This broadness results from the greater background in this case, primarily because the observed process ( $\nu_e C \rightarrow e^- X$ ) gives only one signal instead of the two available in the  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  case. While the fluctuation probability for  $\nu_\mu \rightarrow \nu_e$  is only  $\sim 10^{-2}$ , the two ways of detecting oscillations are essentially independent, providing some confirmation that a real effect is being observed.

### 3 The Need for Two-Neutrino Dark Matter and a Sterile Neutrino

If, as argued above, the atmospheric  $\nu_\mu/\nu_e$  ratio is explained by  $\nu_\mu \rightarrow \nu_\tau$ , one-neutrino dark matter is ruled out, since  $\Delta m_{\mu\tau}^2 \sim 10^{-3} \text{ eV}^2$ . Note that the total neutrino mass needed is  $94 \Omega_\nu h^2 \sim 5 \text{ eV}^2$  for 20% neutrinos and  $\Omega_m = 1$  with  $h = 0.5$ , or  $\Omega_m = 0.6$  with  $h = 0.65$ , where  $h$  is the Hubble constant in units of  $100 \text{ km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}$ . If the LSND result were invalid, three-neutrino

dark matter would be possible, with  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  nearly degenerate in mass.<sup>15</sup> As shown above, however, there is no conflict between the LSND result and other experiments for the mass range desired for hot dark matter.

That leaves two-neutrino dark matter. This scheme<sup>15</sup> requires four neutrinos, with the solar deficit explained by  $\nu_e \rightarrow \nu_s$  (and both neutrinos quite light) the atmospheric effect due to  $\nu_\mu \rightarrow \nu_\tau$  (both of which are heavier and share the dark matter role) and the LSND  $\nu_\mu \rightarrow \nu_e$  demonstrating the mass difference between these two nearly mass-degenerate doublets. Note that the solar  $\nu_e \rightarrow \nu_s$  is for the small mixing angle (or vacuum oscillation), so  $\nu_s$  does not affect nucleosynthesis. The original motivation for this mass pattern<sup>15</sup> preceded LSND and was simply to provide some hot dark matter, given the solar and atmospheric phenomena. If LSND is correct, it becomes the unique pattern. However, just the  $\nu_\mu \rightarrow \nu_\tau$  explanation of the atmospheric result alone forces two-neutrino dark matter.

This neutrino scheme was the basis for simulations<sup>16</sup> which showed that two-neutrino dark matter fits observations better than the one-neutrino variety. The latter produces several problems at a distance scale of the order of  $10h^{-1}$  Mpc, particularly overproducing clusters of galaxies. Whether the  $\sim 5$  eV of neutrino mass is in the form of one neutrino species or two makes no difference at very large or very small scales, but at  $\sim 10h^{-1}$  Mpc the larger free streaming length of  $\sim 5/2$  eV neutrinos washes out density fluctuations and hence lowers the abundance of galactic clusters. In every aspect of simulations done subsequently the two-neutrino dark matter has given the best results. For example, a single neutrino species, as well as low  $\Omega_m$  models, overproduce void regions between galaxies, whereas the two-neutrino model agrees well with observations.<sup>4</sup>

Two-neutrino dark matter requires at least one other light neutrino which must not have the normal weak interaction because of the measured width of the  $Z^0$  boson. Independent information favoring such a sterile neutrino comes from the excellent neutrino laboratory, the supernova.

While  $\Delta m_{e\mu}^2 \sim 6 \text{ eV}^2$  is desirable for two-neutrino dark matter, it apparently would cause a conflict with the production of heavy elements in supernovae. This  $r$ -process of rapid neutron capture occurs in the outer neutrino-heated ejecta of Type II supernovae. The existence of this process would seem to place a limit on the mixing of  $\nu_\mu$  and  $\nu_e$  because energetic  $\nu_\mu$  ( $\langle E \rangle \approx 25$  MeV) coming from deep in the supernova core could convert via an MSW transition to  $\nu_e$  inside the region of the  $r$ -process, producing  $\nu_e$  of much higher energy than the thermal  $\nu_e$  ( $\langle E \rangle \approx 11$  MeV). The latter, because of their charged-current interactions, emerge from farther out in the supernova where it is cooler. Since the cross section for  $\nu_e n \rightarrow e^- p$  rises as the square of the

energy, these converted energetic  $\nu_e$  would deplete neutrons, stopping the  $r$ -process. Calculations<sup>17</sup> of this effect limit  $\sin^2 2\theta$  for  $\nu_\mu \rightarrow \nu_e$  to  $\lesssim 10^{-4}$  for  $\Delta m_{e\mu}^2 \gtrsim 2 \text{ eV}^2$ , in conflict with compatibility between the LSND result and a neutrino component of dark matter.

The sterile neutrino not only solves this problem, but also rescues the  $r$ -process itself. While simulations have found the  $r$ -process region to be insufficiently neutron rich,<sup>18</sup> recent realization of the full effect of  $\alpha$ -particle formation has created a disaster for the  $r$ -process.<sup>19</sup> The initial difficulty of too low entropy (i.e., too few neutrons per seed nucleus, like iron) has now been drastically exacerbated by calculations<sup>19</sup> of the sequence in which all available protons swallow up neutrons to form  $\alpha$  particles, following which  $\nu_e n \rightarrow e^- p$  reactions create more protons, creating more  $\alpha$  particles, and so on. The depletion of neutrons by making  $\alpha$  particles and by  $\nu_e n \rightarrow e^- p$  rapidly shuts off the  $r$ -process, and essentially no nuclei above  $A = 95$  are produced.

The sterile neutrino would produce two effects.<sup>20</sup> First, there is a zone, outside the neutrinosphere (where neutrinos can readily escape) but inside the  $\nu_\mu \rightarrow \nu_e$  MSW (“LSND”) region, where the  $\nu_\mu$  interaction potential goes to zero, so a  $\nu_\mu \rightarrow \nu_s$  transition can occur nearby, depleting the dangerous high-energy  $\nu_\mu$  population. Second, because of this  $\nu_\mu$  reduction, the dominant process in the MSW region reverses, becoming  $\nu_e \rightarrow \nu_\mu$ , dropping the  $\nu_e$  flux going into the  $r$ -process region, hence reducing  $\nu_e n \rightarrow e^- p$  reactions and allowing the region to be sufficiently neutron rich.

This description is simplified, since the atmospheric results show that the  $\nu_\mu$  and  $\nu_\tau$  mix with a large angle, so wherever “ $\nu_\mu$ ” is mentioned, this can equally well be “ $\nu_\tau$ ”. In fact, if the mixing is maximal and the  $\nu_\mu$  and  $\nu_\tau$  mix equally with the  $\nu_e$ , one can show<sup>20</sup> that the  $\nu_e$  flux above the second resonance vanishes totally. To keep the resonances separate and in the proper order, they must occur below the weak freeze out radius, where the weak interactions go out of equilibrium. This requires a sufficiently large  $\Delta m_{e\mu(\tau)}^2$ , and a value like  $6 \text{ eV}^2$  satisfies this requirement, enhancing the argument for hot dark matter.

The near concordance for nucleosynthesis between  $^4\text{He}$  abundance and the D/H ratio alluded to in Section 2 requires that the sterile neutrino not have much effect on  $^4\text{He}$  abundance. The  $\nu_s$  needed for solar  $\nu_e$  depletion does not come into equilibrium in that era, so it has little effect on the expansion rate, but it could cause a  $\nu_e/\bar{\nu}_e$  asymmetry,<sup>10</sup> changing the  $n/p$  ratio and hence altering the amount of  $^4\text{He}$ . A calculation<sup>21</sup> of this effect showed that for this particular model the change in  $^4\text{He}$  was small, possibly being in the right range to correct a small remaining discrepancy, if there really is one.

## 4 Conclusions

A neutrino component of dark matter appears very probable, both from the astrophysics and particle physics standpoints. Despite the evidence for  $\Omega_m < 1$ , the one model which fits universe structure has  $\Omega_m = 1$ , with 20% neutrinos and most of the rest as cold dark matter. Open universe and low-density models with a cosmological constant give extremely bad fits. This conflict should be the source of future progress, but since there are  $10^2/\text{cm}^3$  of neutrinos of each active species left over from the early universe, the ultimate answer on neutrino dark matter will come from determinations of neutrino mass. While the solar and atmospheric evidences for neutrino mass are important, the crucial issue is the much larger mass-squared difference observed by the LSND experiment. In the mass region needed for dark matter, no other experiment excludes the LSND result, if data from the different experiments are compared using the same procedures.

The resulting mass pattern,  $\nu_e \rightarrow \nu_s$  for solar,  $\nu_\mu \rightarrow \nu_\tau$  for atmospheric, and  $\nu_\mu \rightarrow \nu_e$  for LSND, requires a sterile neutrino and provides two-neutrino ( $\nu_\mu$  and  $\nu_\tau$ ) dark matter. This form of dark matter fits observational data better than the one-neutrino variety. Furthermore, the sterile neutrino appears to be necessary to rescue the production of heavy elements by supernovae. This particular mass pattern does not cause any difficulty with the present near concordance in primordial light element abundances, and it could even help if there is a small discrepancy. In short, this four-neutrino pattern agrees with all current neutrino mass information and hence makes more likely the existence of hot dark matter.

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